Bioenerg. Res. (2013) 6:263–275
DOI 10.1007/s12155-012-9255-6

Technical and Economic Modeling for the Production of Torrefied Lignocellulosic Biomass for the U.S. Densified Fuel Industry

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Published online: 23 September 2012
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Abstract During recent years, a renovated interest in the pre-treatment of biomass through torrefaction has led to several proposals on industrial-scale application of the technology. Torrefaction holds promising characteristics for obtaining a high-energy yield biomass for further processing, including densified biofuels such as pellets and briquettes, at low overall costs, low energy input, and high capacity and availability for the near future, having the capability of displacing coal in power facilities. Despite many efforts in developing the technology at an industrial scale, very few manufacturers and companies are offering torrefied machinery and lignocellulosic torrefied biomass. Furthermore, information about the actual profitability of the business, sensitivity, and costs of torrefied biomass are very scarce and are limited to very focused studies in some areas of the production, but not in the overall supply chain, and manufacturing processes. This study aimed to develop and validate a technical and economic model for the production of lignocellulosic torrefied biomass for its utilization in the solid biofuels industry, with a focus on production and delivered costs for U.S. potential manufacturers. This model also includes analysis of important variables affecting production, such as biomass delivered costs, capital expenditure (CAPEX), and technology availability. Results indicate that the production of torrefied lignocellulosic biomass can be profitable for U.S. manufacturers, subject to a high sensitivity on biomass cost, CAPEX, and technology affordability for large-scale production. Other sensitive facts include carbon credits scenarios, which may influence profitability based on analyses of net present value and internal rate of return for the manufacturing facility.

Keywords Torrefaction · Techno-economics · Biomass pre-treatment · Densified biofuel · Lignocellulosic biomass

Introduction

Material that has been torrefied from biomaterials such as wood, grasses, and agricultural waste are regarded as promising solid biofuels and as feed stock for further advanced biofuels [3–5, 15, 35]. Torrefaction is a thermochemical process, or “mild pyrolysis” of biomass in an oxygen-free atmosphere [43]. In this process, there is a degradation of the hydrophilic polysaccharides (complex carbohydrates in wood that interact with water molecules, such as hemicellulose and cellulose) and hydroxyl radicals, resulting in an increase in the percent of lignin content, causing a reduction in the hydroscopicity of the material and an increase in the energy per unit mass, and a carbon-like appearance [19, 26, 31, 38, 43]. The potential attractiveness of using torrefied biomass for solid biofuels is the increase in energy density of the material even at the expense of losing 25–33 % (dry basis) of the original biomass, and 10–20 % of the original energy content [3, 35] through volatilization of CO_2, acetic acid, phenolic compounds, etc. [20, 41, 43], producing a fuel with a high energy yield output. Additional benefits of torrefied biomass include reductions in CO_2 emissions when compared to coal [16] and better grindability properties for co-firing (reducing energy required for grinding of wood particles [2]).

Torrefaction is not a newly developed concept, and its technical principles were first reported in 1930. During the 1980s, it was reexamined in France as a method of producing a biomass-based reducing agent for metallurgic facilities

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(Pechiney Process [5, 7, 8]). This resulted in a demonstration plant operating until the early 1990s. The concept of torrefaction was revived with recent attention given to biomass as a fuel source and is still in either the early development stages (pilot phase) or as a proof-of-concept [38, 51].

One of the main reasons for the lack of large-scale implementation of torrefaction is the scarcity of information on the technical and economic principles that would drive the operation of a commercial facility, including capital investments, production levels, etc. [3, 5, 51]. Jacobs [27] indicated that due to the small number of existing units and their limited scale, the economics of a commercial facility could only be estimated. Previous research work by Bergman et al. [5] was heavily focused on process design and process simulation with Aspen™, and provides background for further economic analyses. There is still a need for further research in the detailed economic aspect of torrefaction including the variables such as the biomass delivered costs, required capital investments, process energy costs, and transportation costs. Previous attempts to describe and assess the feasibility of torrefaction as a pre-treatment have been limited by the lack of data [10], with existent information regarding costs of torrefaction units currently dependent on potential suppliers and start-up companies' estimates. Previous work in evaluating the technical and economic feasibility of factories in Europe producing woody biomass fuels was performed by Pirraglia et al. [37], Mani [30], and Samson et al. [42] on wood pellets, while Bergman et al. [5] and Bridgwater [10] report technical and economic feasibility for the production of torrefied wood in large scale. However, these previous efforts in assessing torrefied wood as a biofuel were performed for European countries scenarios, and further research is needed in describing its possible implementation in the United States and the characteristics of such project.

The objective of this research is to develop and verify a technical/economic model developed in a dynamic spreadsheet-based program that provides detailed information on the feasibility of woody biomass torrefaction based on defined assumptions. The model is intended to provide information on the manufacturing cost structure based on the plant and biomass requirements, capital investments, labor, and the characteristics of the torrefied material. A sensitivity analysis is also conducted on the most significant variables that affect the profitability of the operation.

Methods

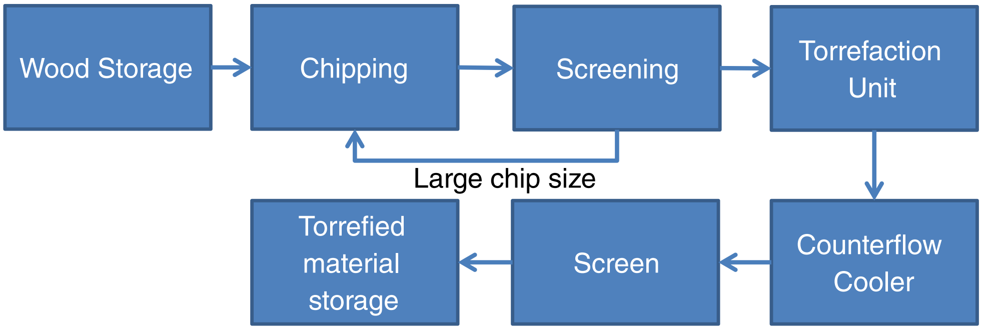
The technical/economic model was developed in dynamic macro-enabled spreadsheets utilizing Microsoft Excel 2010®. A conceptual model similar to that proposed by Pirraglia et al. [37] helped identifying three key areas of development for the model: mass balance, in order to understand and quantify the biomass required by the facility; energy consumption, in order to correctly account for energy consumption and costs utilizing different process configurations and production capacities; and a financial analysis, which integrates all the information from the mass balance and energy consumption and calculates financial indicators such as internal rates of return (IRR), net present value (NPV), minimum revenue, and production costs.

Torrefaction Process

The process of torrefaction is regarded as an accessible technology that is capable of producing a biomass-based energy source with very uniform characteristics [54]. In order to correctly assess the requirements in biomass, capital expenditure (CAPEX), and energy balance for a torrefaction facility, the process must be completely understood. Figure 1 shows the general process for producing torrefied biomass, assuming that the biomass is received as debarked roundwood (debarking included in the biomass delivered cost).

Since biomass contains a great deal of water (moisture), one of the first steps in its conversion is removing water by drying, a process which typically requires high energy inputs [18]. A key element for the successful application of torrefaction is to pre-dry the biomass prior to entering the reactor with the VOCs and off gases from the biomass being treated. Pirraglia et al. [38] and James [28] described a commercial-scale torrefaction unit built and demonstrated at North Carolina State University, with a nominal capacity between 1/2 and 1 metric ton per hour depending on the

Fig. 1 Torrefaction process for a commercial-scale factory producing torrefied wood



biomass type, and which is able to generate more than 80 % of the required process's heat by combusting the VOCs from the biomass, using this heat to pre-dry and remove moisture from the biomass before entering the reactor, and removing VOCs and hemicellulose inside the reactor. Companies such as Biomass Technology Group [11] have proposed processes and machinery for torrefaction with similar principles, using the gases released in the reactor as a heat source, by burning them in a combustion chamber, and producing heat for drying. Bergman et al. [5] also proposed that torrefaction is capable of utilizing the energy content of torrefaction gases to completely produce the heat required for the process and for biomass drying, operating in a point denominated "autothermal operation". A torrefaction factory operating at the autothermal point, with "green" or "wet" biomass received, would not require a separate drying process. Figure 2 shows the biomass and off gases flow in the torrefaction unit. Notice the lack of a separate drying unit, which in the autothermal condition is assumed as a pre-drying sub-process, and consequently, an element inside the torrefaction unit. In the model developed, a detailed assessment of this unit allows to correctly calculate the mass and energy balance necessary for accurate costs calculations.

The structure and process utilized by the torrefaction unit in the model is similar to that proposed by Lipinsky et al. [29] and Topell Energy [47, 48] in which torrefaction off gases are combusted to generate heat for the torrefaction process, as well as residual heat for pre-drying of the biomass before entering the reactor. Three different types of reactors (screw reactor, rotating drum, and moving-bed) can be specified based on the production schemes proposed by Bergman [3]. The type of reactor determines mainly the capital investment and maintenance costs of the unit. Once the proper equipment and flow of biomass through the torrefaction unit is identified, a mass balance can be calculated and automatically adjusted depending on key production variables. The boundaries of the model consider debarked roundwood (cost of debarking included in biomass delivered costs) received in an open-air storage area and a vented load area for trucks after processing the biomass. Hence, the prices and production costs of the biomass reported hereby are considered at the factory gate, ready to ship. The process for torrefaction is linear and is assumed as a best practice, four parallel lines of product being produced at the same conditions [3].

Previous literature [4, 5, 9, 10, 22–25] and previous experience in economic models for biomass facilities [37] aided in the identification of the main production variables required to calculate accurate financial indicators of a torrefaction facility. These are variables that are user-modified inputs of the model including annual production, biomass type and form, biomass moisture content, plant location, and annual production hours per year. In addition to these, torrefaction-specific variables also identified were torrefaction level and carbon credits scenario. These variables are further defined and explained below.

Previous investigations indicate that two critical variables for achieving a specific level of torrefaction and uniform product are the residence time and operating temperature [38]. Researchers report a wide variety of temperatures and residence times [28, 35], varying from 1 min to 35–40 min, and from 200 to 400 °C, although such high temperatures are rarely reached. For this model, experimental data from the NC State torrefaction machine was utilized to define the operating temperatures and residence times. These two

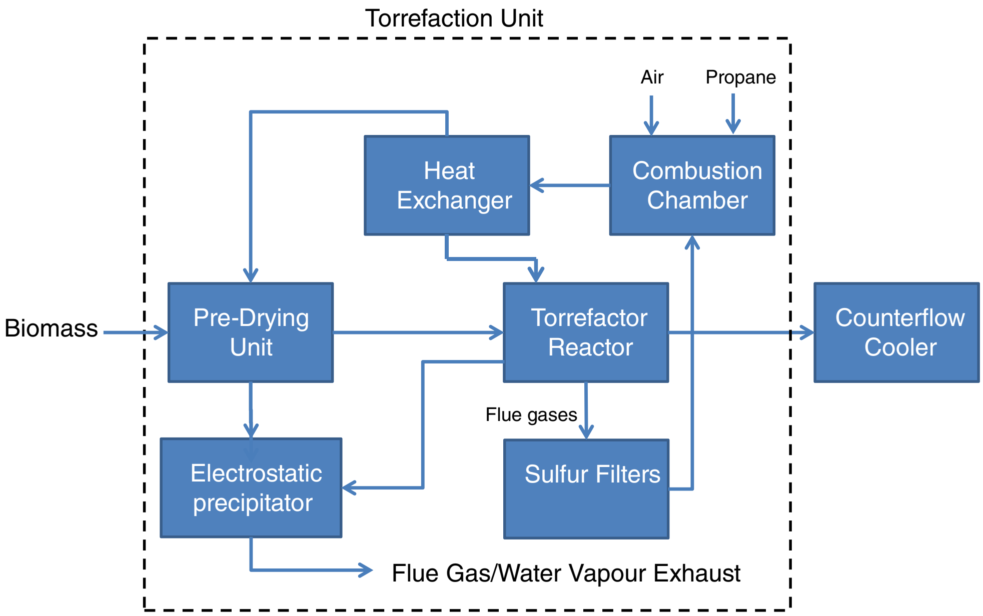


Fig. 2 Schematic detail of the proposed torrefaction unit, including pre-drying

parameters define the "degree" by which irreversible changes are produced in the wood and the amount (% wt.) of VOCs that are released. These parameters define the type of material that will be obtained as a product, and the total output versus the total amount of "green" biomass (mass/mass) that the facility will need. In this work, these two parameters are summarized in a single measure that can be adjusted by the user, denominated "Torrefaction Level". This variable considers three levels of torrefaction, based on experimental information that has been obtained in the North Carolina State University's commercial torrefaction unit: light torrefaction, defined by a short residence time (3 min), and a temperature of 280 °C; medium torrefaction, characterized by a residence time of 4 min and a temperature of 320 °C; and dark torrefaction, with a long residence time (5 min) and high temperature (around 350 °C). In addition, average heating values for woody biomasses (energy density) that can be obtained from each treatment level are displayed in the model (8,458 Btu/lb. for light torrefaction; 9,060 Btu/lb. for medium torrefaction; and 9,502 Btu/lb. for dark torrefaction [28]); actual torrefaction heating values will depend on the biomass used in the unit, and can be modified in the model, which will automatically adjust moisture content (MC) and theoretical energy values (HHV) for the biomass processed. It is important to highlight that testing results from the North Carolina State University torrefaction unit indicate that in order to obtain higher heating values than the average HHV reported in this model, longer residence times at the same temperature ranges should be utilized, with the downside of a reduction in the hourly nominal capacity of the unit (currently between 1/2 and 1 metric ton per hour). Additionally, changes in HHV, MC, and torrefaction level automatically adjust the mass and energy balance of the model. Data from James [28] was utilized in this section.

Mass balance

Detailed mass and energy balances for torrefaction of lignocellulosic biomass have been extensively researched, with various technologies and species evaluated [4, 48, 53]. These investigations have been primarily focused on identifying the chemical composition of the gases released and its relative amount. Part of the information obtained from these previous works (outputs of torrefaction processes as a weight percentage of the biomass being fed) is used to model the mass balance presented in this research.

The mass balance in the model includes user-modified losses (mass %) throughout the production process, with each mass loss initially set at a default value of 0 %, except for the second screening before storage, in which a 10 % mass loss is assumed due to fine and dust particles. Moisture content and VOC losses are automatically re-calculated according to the inputs: annual production, torrefaction level, and working hours per year. The pre-drying process inside the torrefaction unit has the capability of eliminating all moisture from the biomass, being automatically adjusted when moisture content of the biomass as received is changed in the model. The dry biomass enters the torrefaction reactor, and depending on the torrefaction level selected, the mass balance calculates a VOC's elimination from the biomass of 30 % (light torrefaction), 40 % (medium torrefaction), or 50 % (dark torrefaction) of the biomass oven-dry weight.

With this information, flue gases (VOCs) circulating to the combustion chamber and heat exchanger are calculated, as well as the additional energy required (propane utilization in this case, being this a requirement in order to keep a pilot flame that ensures a proper combustion of the gases in the chamber). Based on experimental information from the torrefaction unit being used at North Carolina State University [28], liquid propane utilization in the combustion chamber accounts for approximately 2 % of the flue gases (VOCs) entering the chamber (% weight) and considers the propane/air mixture with 120 % excess air under normal (autothermal) operation conditions (information necessary for energy costs calculations). In addition, the heat exchanger considered for separation of the necessary heat utilized for pre-drying, and for the torrefaction reactor is separated as 20 % (pre-drying) and 80 % (torrefaction reactor) of the mass entering the exchanger, being adjustable if the moisture content of the biomass in pre-drying is increased from the pre-set value of 45 %, requiring more heat in the pre-drying process.

Energy Balance

The most important element of the energy balance for this model is given by the torrefaction unit since this unit requires the necessary heat for pre-drying the biomass and for the torrefaction reaction itself. Under autothermal conditions (and depending on the biomass source), the most important torrefaction product gases, and the ones that contribute to most of the heat generated in the combustion chamber, are usually formaldehyde/acetaldehyde, methanol, pyruvaldehyde/propanal-2-one, furfural, furfuralalcohol, and coniferyl alcohol, among other product gases [39], contributing to the aforementioned 80 % of the heat process (torrefaction and pre-drying).

Although it is stated by several authors that torrefaction in autothermal conditions does not require external energy sources, the authors included a propane pilot flame in order to keep uniformity of the product and reduce the possibility of pressure and heat losses; following guidelines of operation in the commercial scale unit operating at North Carolina State University, this pilot flame contributes to approximately 20 % of the required heat for pre-drying and torrefaction, and for its utilization every time the torrefaction unit requires start-up until reaching autothermal point. Energy (electrical) consumption of the machinery (%) per each ton of torrefied material produced is presented below (Fig. 3), considering that the torrefaction unit utilizes only propane, and that screw systems, fans, and blowers are part of miscellaneous equipment.

Power consumption for the machines (kWh/year) was estimated based on the work of Digiacomo and Taglieri [17], Pirraglia et al. [37], and Bergman and Kiel [4]. Considering the mechanically driven equipment from the torrefaction unit (blowers, fans, screws, etc.) as miscellaneous, it represents the major electrical energy component of the torrefaction facility. With the information of energy consumption for each machine, including potential losses and efficiencies, and the working hours per year, the model calculates the annual electrical and propane consumption, and its associated costs, depending on the plant location, which influences the local unit costs of energy.

Economic Information

Capital expenditure for buildings and machinery, labor, energy, and biomass costs represent the backbone of the model for the accurate calculation of financial indicators. Capital expenditures for machines and equipment were obtained (when possible) directly from manufacturers' information (grinder, screeners, and counter flow coolers), with miscellaneous equipment and installation costs being calculated from literature values [13, 37, 42, 45], and adapted to 2011 values using the Civil Works Construction Cost Index System (CWCCIS) conversion index.

Special attention is given to the costs of a torrefaction unit. Capital costs for a torrefaction facility seem to be highly dominated by the cost of the reactor unit. Previous work on this field indicates that this is a common feature of newly developed torrefaction technologies [5, 10]. Due to the scarcity of potential suppliers of torrefaction units, and the lack of fully operational facilities in existence, it is difficult to obtain accurate market information for torrefaction unit costs and commercial capacities. Instead, some authors have estimated the costs of a torrefaction unit per ton of biomass produced. In this particular aspect, the work of Bergman et al. [5], evaluating a plant producing 200,000 tons/year of torrefied material under European conditions, is extensive and provides one of the few complete costs estimates for the unit, including pre-dryer, reactor, and other equipment, and adding engineering and supervision, installation, and construction expense costs. In addition, three types of technology are considered in their study, with different specific investment costs[1]: screw reactor, with \$32.72/ton (€22/ton) costs; rotating drum with \$23.80/ton (€16/ton) costs; and moving bed, with \$16.36/ton (€11/ton); these estimates are used for the model developed in the present project. The selection of the technology is included as a modifiable feature in the model, adjusting the CAPEX values when modified.

Estimates of the capacity of equipment are adjusted by the model depending on the required annual production, and follows the power law rule proposed by Perry et al. which estates that: $Inv = Inv_L \times (P/P_L)^{0.7}$, where Inv represents the capital investment depending on plant size requirements, $\mathrm{Inv_L}$ represents capital investment of the original equipment, and P and P_L represent the capacity required on the equipment and the capacity of the original equipment, respectively. A scaling factor of 0.7 is used, based on Andersson et al. [1], and on the utilization of four parallel production lines, considered to be running at 80 % capacity. This scaling factor, as well as the estimates on the power rule obtained for capital costs of machinery and equipment, is consistent with class 3 project estimates, following the classification system of AACE,[2] which typically fall within an accuracy range of ±20 % of the costs estimates. Further work and evaluations of torrefaction facilities, especially when new and existent technologies have been scaled up to large commercial sizes and parallel lines can be reduced, will involve and require refined estimates, for which the scaling factor would be closer to unity, and its application reduced to less significant equipment and machinery of the project. In addition, such refinement of estimates and elimination of parallel lines in the future will possibly reduce the capital

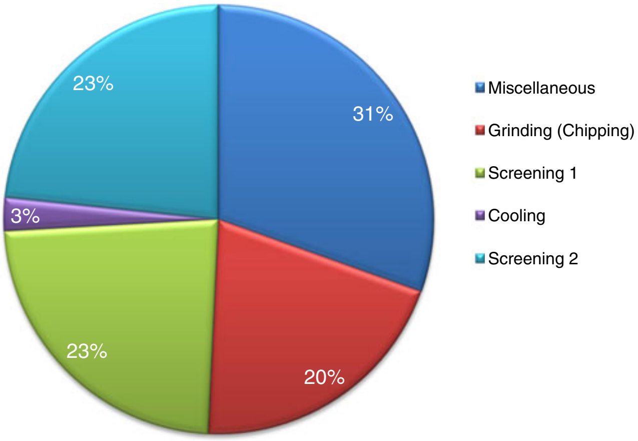


Fig. 3 Distribution of electricity use in the factory by machine. Considering the torrefactor mechanical systems as part of miscellaneous equipment

costs significantly, increasing the likelihood of a torrefaction project.

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[1] 2005 average €/\$ conversion rate, and adjusted to 2011 dollar values with CWCCIS Index

[2] Association of the Advancement of Cost Engineering, Cost Estimate Classification System as applied in Engineering, Procurement, and Construction Industries.

Indirect and contingency costs are calculated as 24 % and 10 %, respectively, of the facilities and machinery total installed costs, as proposed by Woodworth et al. [52]. Storage capacity is necessary for the biomass entering the facility, and after production, torrefied biomass is directly dumped in delivery trucks/railroad, assuming a bulk-delivery selling strategy. Warehouse costs represent 7.6 % of the total plant building space [45]. Plant and equipment depreciation is calculated using a MACRS-7 method (Modified Accelerated Cost Recovery System, in 7-year class, which depreciates 14.29 %, 24.49 %, 17.49 %, 12.49 %, 8.93 %, 8.92 %, 8.93 %, and 4.46 % each year from the total assets value in seven years).

Labor costs per occupation and headcount are calculated based on data for annual mean wages and salaries from the Bureau of Labour Statistics [12]. In addition, a labor structure similar to that proposed by Campbell [13] is used. According to Bridgwater [10], a torrefaction facility has very few labor requirements. Based on this information, the model calculates an estimate of direct labor and indirect labor adjusted to the size of the facility (annual production), and working hours per year, following the guidelines used by Pirraglia et al. [37].

Biomass costs (user-modifiable variable) at plant gate were established at $45 per bone dry ton (BDT, as an average delivered cost for softwoods and hardwoods), with an annual cost increase of 1 %, with lower values than previously reported by Gonzalez et al. [21] and Pirraglia et al. [37], following a slight price decline that has been common during most of the year 2011, and more consistent with values from Forest2Market analyses [34, 44], and with values recently reported by Nielsen-Pincus et al. [33]. Initial assumptions of the model include a bulk delivery strategy of the finished product, reducing the consumables needed at the facility, having only plant and office tools, lubricant and spare parts for the torrefaction unit, and other equipment, estimated at $3.00/ton. Additional costs include marketing/sales fees and incentives, maintenance and repairs, and forklift operating costs, estimated at $6.00/ton, $8.85/ton, and $0.17/ton, respectively [5, 13].

Results and Discussion

In order to further analyze the characteristics of a U.S. torrefied wood manufacturer, a case study is presented. In this case study, a factory producing 100,000 tons/year of torrefied biomass is considered. Table 1 summarizes the main parameters considered for the case study.

In addition, the facility considers a scenario with no carbon credits placed (although alternate scenarios are considered, according to estimates by Childs [16]). The size of the facility was selected to match similar proposed studies, in order to present results that may be comparable with similar research projects. Characteristics and estimates are similar to those reported by Topell Energy [48], in their analysis of a 100,000 tons/year plant, especially in terms of capital investment, sales price, and labor estimates.

Table 1 Parameters utilized in the case study factory

Parameter	Value
Annual production	100,000 tons/year
Required raw material (green)	238,096 tons/year
Initial moisture content	45 %
Final moisture content	5 %
Heating value of product	8,458 Btu/lb.

At this point, it is relevant to discuss some previous models developed for biomass torrefaction plants; Björklund [6] indicated that a pre-feasibility study was performed in 2010 for a Metso factory producing 200,000 tons/year, utilizing a similar screw reactor directly heated, concluding that prices for a torrefactor units were still out of reach from an economic standpoint, and it required more technical demonstration. Mitchell et al. [32] also performed a simulation of processes and costs for a factory producing 80,000 tons/year of torrefied wood. Other smaller sized factories have been proposed and analyzed, such as Topell Energy [46], started production tests in a torrefied wood factory in Duiven, Netherlands, with a capacity of 60,000 tons/year; Metso proposed a 30,000 tons/year plant to be commissioned during 2012 [6], and Radian Bioenergy has completed preliminary engineering on a torrefaction system [36], however, few details are provided in the analysis of technical and economics of each proposal.

Energy Usage

The plant site (for electrical and propane costs effect) is considered as the average of U.S. electrical costs for plant locations, although the model is capable of selecting specific state locations with its associated local energy costs. Additionally, a screw reactor technology was selected for the torrefaction unit. For further analyses (sensitivity to type of unit), other options are considered. Table 2 shows the results for energy consumption and costs in the case study.

Energy usage in the facility represents a drastic reduction in costs as compared to other biomass pre-treatment options such as wood pellets. Pirraglia et al. [37] reported energy costs of $2,854,532/year for a similarly sized factory, representing an energy cost reduction of approximately 69 %, mainly due to the elimination of a separate drying process.

Table 2 Electrical and propane usage and costs for the case-study factory; electricity and propane costs are obtained from the U.S. Energy Information Administration [49, 50]

Propane usage (gallons/year)	222,837.00
Propane cost ($/gallon)	3.00
Total propane costs	299,939.00
Electricity usage (kWh/year)	9,380.95
Electricity cost ($/ton)	6.71
Total electrical costs	670,785.00

The facility is assumed to run with four parallel lines producing the material, as recommended by Bergman et al. [5]. Current capacities and availability of commercial torrefaction equipment is low, rarely exceeding 3–5 tons/h, and the scalability and product consistency for larger sized machines is still unclear, thus, requiring more than a single large-scale torrefaction unit in place for full capacity production. These reasons justify the use of four parallel product lines with smaller torrefaction units in order to reach full capacity, instead of utilizing a single line with a large capacity torrefaction unit. This implies (for CAPEX calculation effects) that there is a fixed number of machines (four of each type, and its respective feeding system, conveyors, and miscellaneous equipment), and the capacity required from each machine will vary depending on the annual production. Once torrefaction units have reached higher capacities, and the different technologies have been field-tested in large scale, single large-scale production lines could become a better option instead of separate lines, reducing CAPEX needs and floor space in the facility. Based on the case study and its mass balance, each torrefaction unit must be able to process 44 tons/hour (output) in order to meet production requirements. In this sense, the costs for a torrefaction unit were estimated by Bergman et al. [5] as $32.72/ton (€22/ton), which is converted to US dollars per ton considering the average euro–dollar exchange rate of 2005, and using the CWCCIS Index for extrapolating the unit costs to 2011 values. CAPEX calculations are presented below (Table 3).

CAPEX of the facility are represented in its majority by the costs of the torrefaction unit, representing approximately 60 % of the total installed costs. Such high percentage is considered as a first-plant cost, in which as subsequent plants are built, capital costs of the new technology can follow the rule that capital costs may be reduced by 20 % for every doubling of the number of plants built [10].

Operating costs of the facility include direct and indirect labor, totaling 33 operational and administrative personnel, with three shifts per day, and also includes consumables and additional costs. A summary of operating costs is presented in Table 4.

Additional costs include, as mentioned in the "Methods" section, marketing/sales fees and incentives, maintenance and repairs, and forklift operating costs. Labor structure, as calculated by the model, includes one supervisor, four production employees, one forklift operator, one maintenance technician, and one raw material employee for direct labor, while administrative personnel is composed of two accountants, two sales/marketing representatives, one executive/administrative assistant, one finance manager, and one general/production manager. Total production costs are in its majority dependent on the biomass delivered cost. Figure 4 summarizes the main elements that compose production costs of torrefied wood.

Production costs for a 100,000 tons/year case are $193.53/ton and are slightly higher than values reported from other independent studies. Mitchell et al. [32] found costs of 199, 149, and 120 $/ton,[3] depending on the biomass source (Sawmill co-products, Forest Residues, and wood processing co-products, respectively). Cerezo [14] reports a cost of $134.83/ton for torrefied wood under a minimum cost scenario, while Topell reported $169/tons for torrefied wood pellets [48].

Biomass costs (at $45/BDT) represent 37 % of the total production costs, followed, in decreasing order, by depreciation (29 %), labor (13 %), additional costs (10 %), energy (6 %), and consumables (5 %). Contrary to other studies in biomass fuels [37], energy costs represent a smaller fraction of the total production costs (6 % vs. 17 % for wood pellets), mainly due to the elimination of a separate drying process and the autothermal operation of the torrefaction unit; however, this variable requires further detailed study since drying activities are mostly based on biomass burning to generate the required heat for drying, thus affecting or influencing the biomass costs and requirements, while torrefaction makes use of flue gases recirculation and a pilot propane flame. Thus, a detailed analysis of torrefaction and drying technologies with its respective energy balances will allow for a direct comparison of energy consumption and more accurate estimates.

Production costs are calculated in the income statement, with MACRS-7 depreciation, and a CAPEX spending schedule of 20 %, 40 %, and 40 % in 3 years (2011–2013). Add-ins and macro-enabled functions in the income statement allow to adjust the production costs to obtain specific IRR, at a discount rate set at 12 % (also modifiable). In Fig. 5, the minimum revenue and net present value of the facility are presented, adjusted to IRRs ranging from 6 % to 14 %.

Back-calculated prices of torrefied wood with current conditions indicate that selling prices at factory gate (bulk delivery) must be higher than $216/ton in order to obtain positive NPVs (12 % IRR). With this adjusted minimum

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[3] Values reported were converted from 2007 €/$ (euro to dollar) average conversion rate, and transformed to 2011 dollar values with CWCCIS Index.

Table 3 CAPEX for the case-study facility

Item	Number required	Cost per each equipment	Installation cost	Total equipment costs	Total installation costs	Total equipment+ installation costs
Misc. conveyors	8	15,188	7,594	121,508	60,754	182,262
Front-end loaders	2	22,783	0	45,565	0	45,565
Feed hopper	20	7,594	4,557	151,885	91,131	243,016
Grinder	4	766,126	113,914	766,126	455,654	1,221,780
Torrefaction unit*	4	7,297,615	0	29,190,459	0	29,190,459
Live bottom bin	20	18,226	15,188	364,523	303,769	668,293
Counter flow cooler	4	150,000	18,226	600,000	72,905	672,905
Screener 1	4	15,188	12,151	60,754	48,603	109,357
Screener 2	4	15,188	12,151	60,754	48,603	109,357
Fork lift	2	22,783	0	45,565	0	45,565
Site and site preparation	1	156,000	0	156,000	0	156,000
Paving/receiving station/load area	1	60,000	0	60,000	0	60,000
Building and office space	1	1,020,000	0	1,020,000	0	1,020,000
Total				32,643,139	1,081,419	33,724,559
Storage warehouse						77,622
Indirect costs (24 %)						8,112,523
Contingency (10 %)						4,191,470
Total installed costs						46,106,174

revenue as a baseline, potential revenue margins of $22.37/ton can be obtained for producers (at $193.53/ton production costs). This minimum revenue is assumed to be at the facility exit (distribution docking); assuming that the torrefied material is loaded in trucks for its distribution (20 tons/truck capacity [40]), and that the biomass travels a maximum distance of 50 miles, a simple transportation cost may be added for calculating the delivered cost of torrefied material to power and co-firing facilities. Following the transportation model of Brechbill and Tyner [9], with a fixed cost of $15/ton of biomass, and a variable cost of $0.12/ton, a delivered ton of torrefied wood reaches $237/ton at power plant gate ($216/ton price at factory gate, plus $21/ton for transportation within a distance of 50 miles). This delivered price is similar to other biomass pre-treatment options such as wood pellets (at $244.3/ton [37]), representing a potential alternative option for biomass power plants in terms of delivered costs. The potential of combining these technologies, hence eliminating the drying process in pelletization, and combining other processes, represents a promising combination of pre-treatments that needs to be further evaluated. In addition, further work is required in order to evaluate the profitability of shipping torrefied biomass to European markets, considering that it will require port warehousing and fees, maritime transportation, and additional variables that may influence profitability, such as bonuses for high

Table 4 Operating costs for the case-study facility

Operating cost	$/year
Direct labor	1,274,765
Indirect labor	697,829
Consumables	794,285
Additional costs	1,502,043
Total operating costs ($/year)	4,268,922

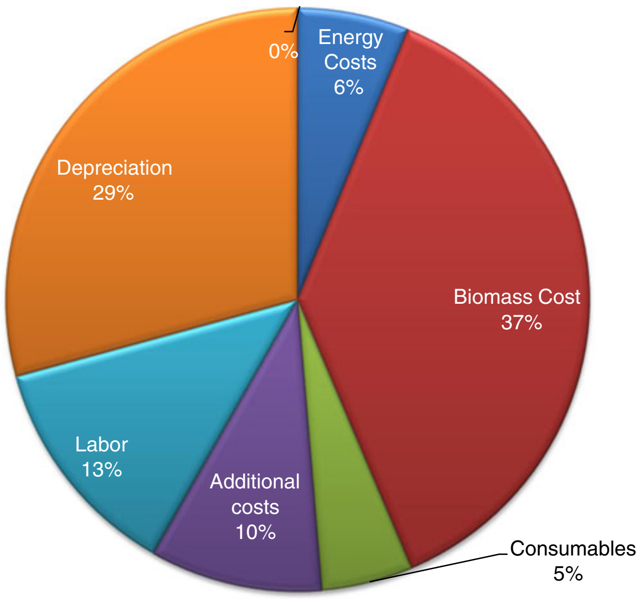

Fig. 4 Production costs distribution according to results from the model

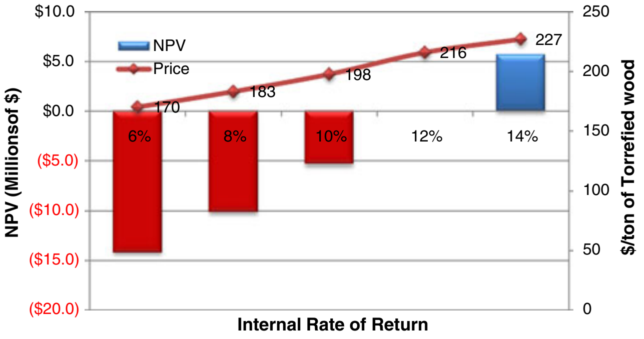

Fig. 5 Torrefied biomass price and NPV changes at different IRR

delivered heating values and low moisture content of the biomass.

An additional aspect that requires in-depth evaluation is the economy of scale for torrefaction facilities, and how the increase in size of these will influence the delivered price of torrefied woody biomass, as well as other critical economic variables. Such analyses should consider transportation costs for bulk delivery, and also a comparison between torrefaction and alternative pre-treatments such as wood pellets, torrefied wood pellets, chipping, and drying, to determine in which scale torrefaction is economically attractive. Such analyses are currently being developed by the authors.

Sensitivity Analysis

In order to evaluate the economic feasibility of a torrefied wood facility, the sensitivity of the project to several critical variables must be assessed. In the case study presented (100,000 tons/year), the NPV and IRR are monitored while changing (increasing and decreasing) variables such as CAPEX, energy consumption, labor, and biomass costs. A fixed minimum revenue of $216/ton was selected, being this the adjusted price for obtaining a 12 % IRR (12 % discount rate), and the variables were modified by ±25 % of its current value. Figure 6 demonstrates the most sensitive variables of the model in which CAPEX produces the largest changes in minimum revenue, being biomass the second most sensitive variable. More detail on the changes produced in the IRRs and NPVs of the facility for each one of the sensitive variables is presented in the next paragraphs and figures.

The current case study is particularly sensitive to changes in CAPEX in which the IRR fluctuates from 19 % to 10 % and the NPV from $11,072,595 to −$7,513,473. This variable presents larger differences in IRR and a steep decrease in NPV as the CAPEX are increased (Fig. 7).

Although CAPEX changes seem to have large effects in IRRs and NPVs, the torrefaction technology, a major technological component of the investment, may produce the majority of these effects. The torrefaction unit represents approximately 60 % of the total capital investment, and changes in the type of technology used greatly affect the overall capital investment of the facility. Figure 8 presents the sensitivity of the project to changes in the torrefaction technology used, having as base case the screw reactor (assumed as the standard unit in the case study since it represents a well-studied technology concept for torrefaction [5]), and without any other variable changes.

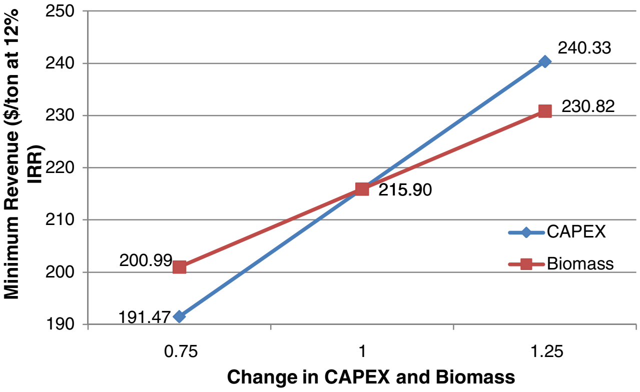

Fig. 6 Sensitivity of the minimum revenue to changes in CAPEX and biomass delivered cost

Screw reactor is an indirectly heated technology in which hot gases and/or other heat transfer media (such as an oil jacket) circulate heat outside the screw system, heating the biomass that is moving inside the screw. Rotary drum technology is a directly heated method based on flue gas recirculation in a rotary drum, which heats the biomass by establishing a direct contact between its surface and the gases. Moving bed reactor is another directly heated method in which a blower supplies hot gas to the reactor and the biomass is heated in a moving conveying system, which optimizes heat transfer rates and provides for a compact design [5].

The selection of a screw reactor, rotating drum, or moving bed reactor technology has a large effect in the IRR and NPV of the facility. Since rotating drum and moving bed reactor have lower investment and installation costs, these

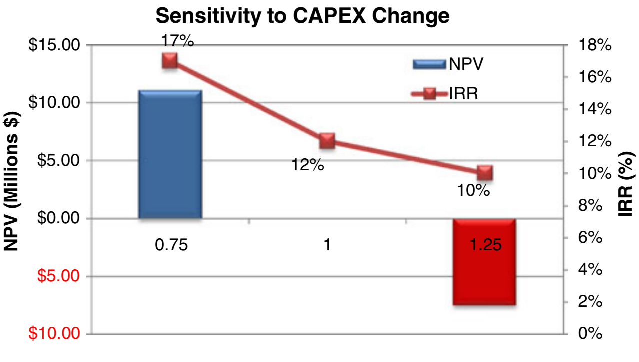

Fig. 7 Sensitivity of the model to changes in CAPEX

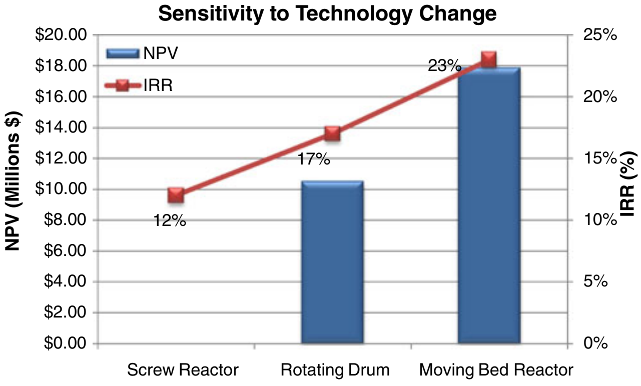

Fig. 8 Sensitivity of the model to changes in the torrefaction technology used

options greatly enhance the profitability of the facility. However, these technologies have only been tested in laboratory scale, while screw reactors have been tested in pilot facilities and ramp-up production runs, and its upgradability and associated costs are uncertain, in which case a screw reactor represents the most proven technology for a large-scale application at this moment. Further detailed analysis of scalability, risk assessment, maintenance costs, production rates, product quality, and availability of suppliers for these technological options must be evaluated in order to accurately calculate the influence of the type of reactor in the total capital expenditure of a factory.

Biomass delivered cost is the second most sensitive variable of the model, drastically affecting the NPV of the project (−$3,438,522) if biomass costs are increased 25 % and greatly increasing the suitability of the facility if biomass costs are lower than current evaluated costs ($33.75/ton; NPV=$7,061,525). Figure 9 shows the changes produced and its effect in IRR and NPV.

These results are in concordance to the breakdown of the production costs of torrefied wood (presented in Fig. 4), in which biomass cost represents 37 % of the total production costs. Since biomass represents such a major component of the production cost (37 %), minor changes in raw material delivered costs have major effects in the profitability of the business.

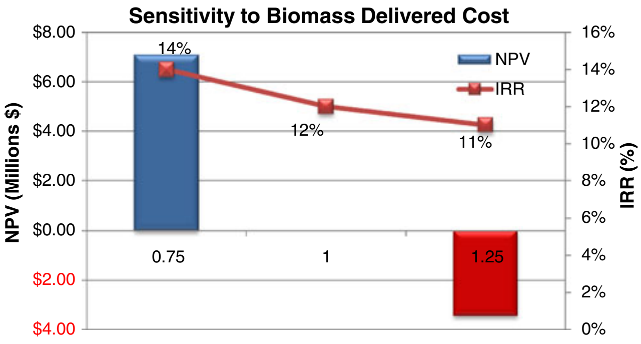

Fig. 9 Sensitivity of the model to changes in delivered cost of biomass

The rest of the variables evaluated (energy costs and labor costs) present a less noticeable fluctuation in the IRRs and NPVs obtained, and might not represent a large sensitive factor. Mainly, energy costs remain low due to the elimination of a separate drying process and the autothermal operation of the torrefaction units. Labor costs have a small effect in the overall financial indicators due to the small direct labor requirements of such facility. In both cases, the IRR is not significantly affected (14 % in all cases), and the NPVs are only slightly modified by ±$100,000. This represents a significant difference compared to similar analyses of biomass pre-treatments, in which labor and energy costs are sensitive variables affecting profitability [23, 25, 37].

Additional Analysis

The possibility of benefiting from a carbon credits market is an important factor that needs further development and analysis in the profitability of a torrefied wood facility in the U.S. Integro Earthfuels [16] estimated that torrefaction companies in the U.S. could benefit from carbon credits in a range between $36/ton and $72/ton of torrefied wood produced, depending on the final characteristics of the product. Different scenarios were developed in order to make a preliminary comparison of how an increase or decrease in the carbon credits market may influence the financial indicators of the facility. Figure 10 shows the different scenarios evaluated at $0/ton (base case), $36/ton, $54/ton, and $72/ton of carbon credits, and its respective NPV and IRRs.

The increase or establishment of a carbon credits market produces a largely positive NPV and a considerable increase in the IRR of the project. In this sense, price increases in the carbon credit market ($54/ton and $72/ton) highly enhances the profitability of the business by increasing its net present value and internal rate of return. This exploratory analysis indicates that carbon credits may become a key variable for investors in new torrefaction facilities, and leaves ground for further research in this area, in which risk assessment has to be

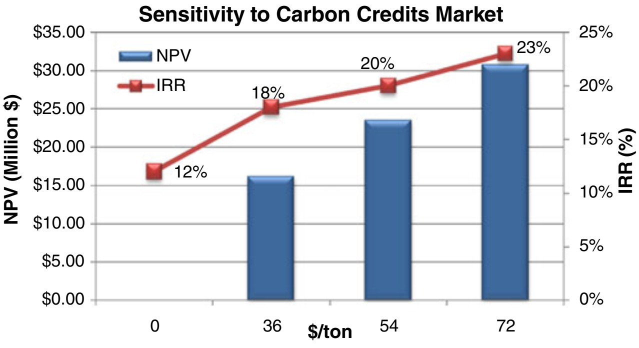

Fig. 10 Sensitivity of the project to different carbon credits scenarios

considered, as well as uncertainty, market fluctuations, and new regulations that may apply for U.S. producers.

Conclusions

A dynamic, spreadsheet-based model was created in order to evaluate and integrate the technical and economic variables and parameters of a biomass torrefaction facility, with the specific aim of U.S.-based facilities with bulk delivery strategy, and intended for co-firing in power facilities. The information provided by the model (price in dollars per ton of torrefied material) is similar to other studies proposed and indicates its accuracy in predicting financial and technical conditions for a facility. In addition, a sensitivity analysis for changes in the key variables of the model was performed. Results from the model and its sensitivity analysis indicate that:

- Minimum revenue (back calculated) for torrefied wood in order to obtain at least a zero NPV (break even, with 12 % IRR) must be higher than $216/ton, providing a potential revenue margin of $22.37/ton for producers, although higher expected IRRs are recommended, such as 14 % (producing an NPV of $5,702,000). Torrefied material delivered cost to power plants (co-firing) may reach $237/ton with a maximum hauling distance of 50 miles. This technology may be competitive (cost-wise) with other biomass pre-treatment options (pellets, briquettes), and a combined-facility analysis is recommended in order to evaluate the potential profitability of combining these two biomass pre-treatments for further biomass enhancing. Further analysis is required for the profitability of delivered cost of torrefied biomass for European markets, which should include maritime transportation, port warehouse space and fees, and bonuses for delivered heating value.
- Energy usage (electricity and propane) in a torrefaction facility operating under autothermal conditions is greatly reduced (nearly 60 % costs reductions), as compared to other options for biomass pre-processing into solid fuels, such as wood pellets and briquettes; minimizing the impact of drastic changes in energy costs in the production costs, NPV, and IRR of the business. Further analyses of torrefaction technologies vs. drying technologies with its respective mass and energy balances with associated costs will allow for more accurate estimates for energy consumption and are highly recommended for future work.
- CAPEX represent a highly sensitive variable for a torrefaction factory. Changes in CAPEX can largely affect the NPV of torrefaction. One of the most important factors contributing to a high sensitivity of CAPEX is the torrefaction technology used. The selection of new technologies may highly increase the profitability of torrefaction, however, more technical information about scalability, product throughput and output quality, capacities, and maintenance must be evaluated before deciding the implementation of these technologies.
- Biomass cost represents the second most sensitive variable of the model for a torrefied wood facility, and will likely influence location near the biomass basket, since it represents the major component of the production costs (37 %).
- The addition of carbon credits to the financial indicators of a torrefaction facility may become a key element if the market finds the right set of conditions and regulations in the U.S. Preliminary analysis indicates that an increase in carbon credit prices may drastically benefit the torrefied biomass business.

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